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Forced air flow through a rectangular channel with 3D turbulence enhancers: fluid-dynamics and thermal analysis by Large Eddy Simulations

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Abstract. Many newer engineering applications, like the cooling of automotive batteries and high-performance CPUs, require heat exchangers (HEs) with large contact areas and very small heights. Performances of this type of HEs can be significantly improved by using surfaces enhanced with optimized 3D structures. The project Mood4hex aims at designing new geometries with optimized morphology, starting from a large database of experimental data on ribbed surfaces. In order to perform an optimization algorithm on such surfaces, analyses are carried out on CFD models with increasing complexity and computational time, to find a fast-running code that preserves the physical meaning. Until recently we used RANS models, and now we began to investigate the use of Large Eddy Simulations (LES) as a higher order validation tool for simpler models. In this paper, we present the results of LES along with experimental data of a forced air flow inside a streamwise periodic rectangular channel of high aspect ratio, i.e., 1:10, equipped with standard transverse ribs ($\alpha = 90°$). More specifically, the ribs are placed only on the lower wall that is operated at constant heat flux, while air flowing at Re 500 or 1000. Comparison of experimental data vs LES results shows weaknesses and strengths of the model.

1. Introduction

In the framework of new enhanced surfaces for ultimate generation heat exchangers, the HEs with large contact surfaces and very small heights are seeing wide application areas in cutting-edges cooling applications like automotive batteries and high-performance CPUs [1]. This work positions itself in the first steps of the project Mood4hex that, as final objectives, aims at designing new geometries with optimized morphology. After investigating by means of RANS simulations, in this paper the first results obtained by Large Eddy Simulations (LES), as a high order validation tool for traditional ribs, are presented.

As reported in [2], RANS simulations have been recognized for their limitations in accurately modeling large, unsteady features, such as separation. In contrast, LES offer a more detailed representation of fluctuating components along with mean quantities. Despite the typically higher computational cost of LES compared to RANS, the former allows to obtain more precise and comprehensive results, and hence a deeper understanding of the involved physical phenomena also regarding heat transfer.

So, in the context of fluid-dynamic simulations, the presence of ribs in channels introduces a complex interaction between fluid flow and solid boundaries. LES stands out for its enhanced accuracy in handling flows confined by walls. In ribbed channels, where the impact of ribbed surfaces on the flow is crucial, LES ability to capture these turbulent features becomes particularly significant.

The drawback of using LES is the computational cost but, if feasible [3], it is possible to apply LES to a periodic domain or using a hybrid RANS-LES approach.

The calculus domain considered here does not reproduce the whole experimental channel, but it's a 3D periodic domain in streamwise direction, with a rectangular cross section of the same aspect ratio (AR) of 1:10 yet, equipped with standard transverse ribs ($\alpha = 90°$, figure 1). The ribs have a square cross section, with a side-to-channel-height ratio of 1:3, and they are equally spaced with a non-dimensional pitch $p/e = 20$, figure 3.

2. Problem configuration and methods

Two experimental setups have been used, namely, one for the fluid-dynamic analysis and another for the thermal analysis, both with a rectangular cross section of 12mm x 120mm equipped with square cross section ribs, 4mm high and 120mm long. The length of the channels and the number of ribs depends on the experimental setup considered. In the following, first we present in detail the two experimental setups, and then the numerical model.

2.1. Experimental setup for fluid-dynamic analysis

The channel used for the fluid-dynamic analysis is made of Plexiglas with transparent finish, equipped with few transverse ribs ($\alpha = 90°$) on the lower wall. Plexiglas has been chosen to allow image shooting of the flow by means of a high-frequency digital camera. The camera frame rate comes out from a balance between image brightness and their blurring that must not prevent the capture of the fluid motion details. The channel has smooth walls, sufficiently long to allow the hydrodynamic development of the flow; beyond this region, some ribs are mounted on the lower wall. The area captured by the camera starts beyond the second rib. The flow is visualized using as dye a very fine water mist or smoke, injected at the channel inlet, while lighting the area to be analysed by a laser sheet. Thanks to this experimental setup we collected images of the flow field between two consecutive ribs in the following selected cutting planes: mid-plane (x, y) of the spanwise dimension z, and a plane (x, z) placed at $y = -4mm$ intersecting the ribs at their half (the origin of the axis is in the center of the cross section). This experimental setup

Figure 1. $\alpha = 90°$ ribs configuration.

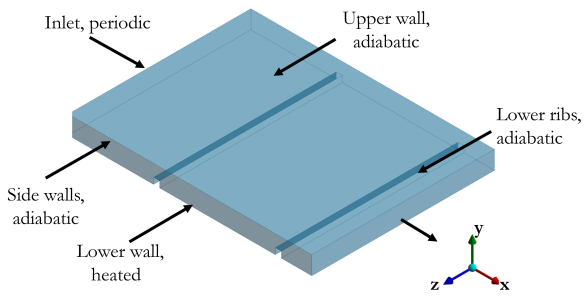

Figure 2. Fluid domain, 3D periodic channel.

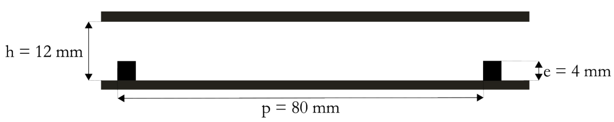

Figure 3. Main geometric parameters.

has been described in [4].

2.2. Experimental setup for heat transfer analysis

In order to investigate heat transfer, a different experimental setup is used, yet exploiting a narrow rectangular channel with AR= 10, with adiabatic ribs (in $\alpha = 90°$ configuration) mounted on the lower wall, that is operated at imposed heat flux. As the Authors are involved in a long-term ongoing study on forced convection at ThermALab laboratory at Politecnico di Milano, this experimental set-up, along with measurement methods, is detailly described in [5]. Worth mentioning is the presence on the upper wall of the channel of an optical access for IR measurements. It consists in a germanium window that allows to obtain IR images which provide data on local convective heat transfer coefficient of the lower wall. IR images need to be carefully processed in order to obtain initially the real temperature field and then the local convective heat transfer coefficient of the lower wall of the experimental channel. The procedure that leads from the IR image to the temperature field and subsequently to the local convective heat transfer coefficient of the wall under examination has been explained step by step in [6].

2.3. Numerical model

The computational domain consists of a 3D periodic channel in the streamwise direction, with a rectangular cross section of AR = 1:10 equipped with transverse ribs ($\alpha = 90°$). Performing a simulation on a periodic domain does not introduce any significant error because in the experimental channel, the thermal development of the flow occurs after a certain distance from the inlet and where experimental measurements are taken, the flow is thermally fully developed. Numerically, it is thus possible to conduct LES and go into the details of flow and temperature fields. The working fluid is air, incompressible and with a turbulent flow regime, $Re = 500$ and $Re = 1000$, due to the presence of ribs.

Regarding boundary conditions, the channel has periodic inlet-outlet sections, imposed heat flux on the lower wall, while ribs and other walls are adiabatic (figure 2). It was chosen to work with a periodic domain containing two ribs. We asked ourselves how the choice of a more or less extended periodic domain (in streamwise direction) affects simulations and/or changes the presence of vortex structures. Since this is a preliminary study, limited by the requests of the experimental setup, and since further studies will be conducted on higher Reynolds numbers, we focused on creating a simple model that did not require excessive computational effort. The choice fell therefore on a periodic domain with two ribs since it allows to have double the domain under investigation so that, if some turbulence structures appear between them, they have space and it's required a reasonable computational effort. For higher Reynolds numbers we plan instead to carry out a sort of domain sensitivity analysis, but for the moment the choice falls on this domain, although aware of possible limits.

As concerns the choice of the sub-grid viscosity model, Dynamic Smagorinsky has been chosen because although the studies found seem to struggle to find a better model than the others, some authors among which Fatica et al. [7] and Ciofalo [8] found that the Dynamic model predictions are slightly more regular and in better agreement with the DNS (Direct Numerical Simulation) data.

Regarding the grid scale, calculating analytically the dimension of the smallest elements of the computational grid could give an indication of what fraction of the turbulent kinetic energy is resolved [8], for this work the choice fell on a grid that resolves at least the $92\% - 96\%$ of the turbulent kinetic energy spectrum. If the choice of this grid scale is appropriate will be investigated further on the basis of the results that will be obtained.

Courant number has been maintained below 0.67 requiring reasonable computational time, using from 4 to 12 cores Intel(R) Xeon(R) Gold 6148 CPU @ 2.40GHz.

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3. Results

3.1. Fluid-dynamic analysis

Regarding fluid-dynamics, experimental and numerical velocity fields have been compared qualitatively on different cutting planes in order to start investigating their agreement.

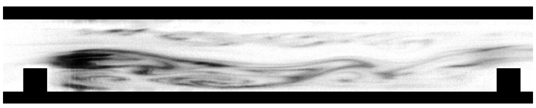
We selected two different cutting planes, one along the centre line of the channel, mid-plane (x, y), to capture the motion evolution in the streamwise direction (z), and the other placed in the y, z plane at a distance $y = -4mm$ from the origin of the axes (placed in the centre of the cross section) which intersects the ribs at half their height. Two different Reynolds numbers have been considered, i.e., $Re = 500$ and $Re = 1000$. In figure 4a and figure 4b it's possible to qualitatively compare the instantaneous velocity field on the mid-plane for $Re = 500$, whereas in figure 4c and 4d the instantaneous velocity field on the mid-plane is shown for $Re = 1000$. Finally, in figures 4e and 4f, the comparison between instantaneous velocity field at plane $y = -4mm$ for $Re = 1000$ is shown. At Reynolds number 500 the comparison is quite poor. The numerical model failed to capture the majority of turbulent structures with the exception of the re-circulation vortex after the rib. At $Re = 1000$ the numerical model managed to capture turbulence structures in addition to the main vortexes.

3.2. Heat transfer characteristics

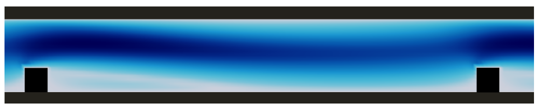
Regarding heat transfer characteristics, the agreement between numerical and experimental distributions of local Nusselt number on the lower wall has been compared qualitatively.

Regarding heat transfer characteristics, agreement between numerical and experimental distributions on the lower wall of the local Nusselt number has been qualitatively analysed.

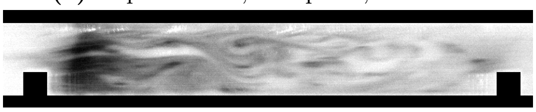
Numerically, the local Nusselt number has been obtained from the bulk temperature along



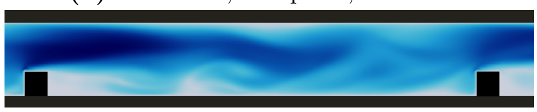
(a) Experimental, mid-plane, $Re = 500$.



(b) Numerical, mid-plane, $Re = 500$.



(c) Experimental, mid-plane, $Re = 1000$.



(d) Numerical, mid-plane, $Re = 1000$.

(e) Experimental, plane $y = -4mm$, $Re = 1000$.

(f) Numerical, plane $y = -4mm$, $Re = 1000$.

Figure 4. Instantaneous velocity fields.

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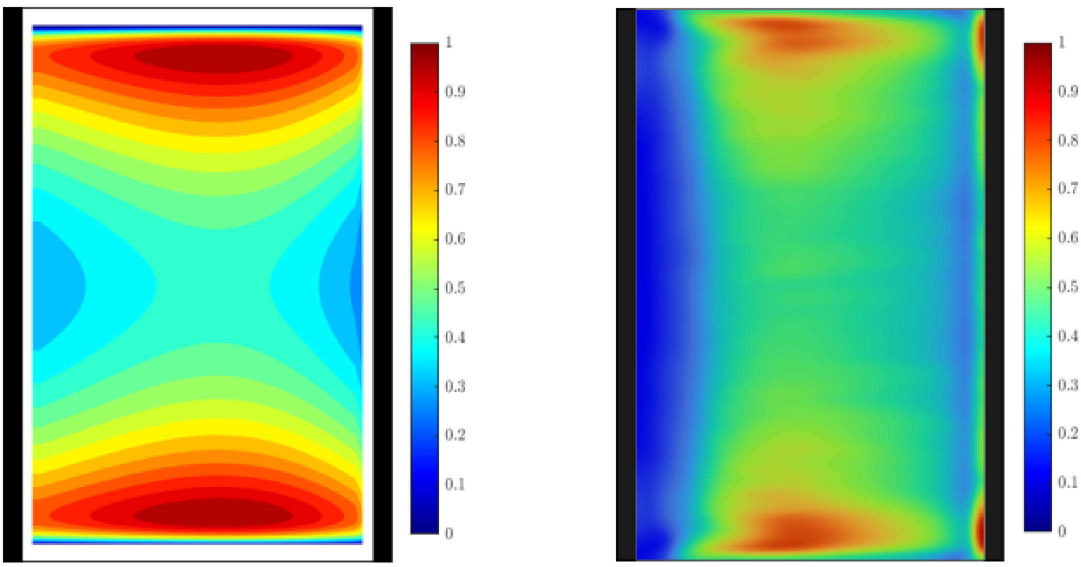
the channel T_b, the local temperature on the lower wall T_{wall}, and the heat flux q imposed on the lower wall. Values of the bulk temperature have been evaluated along the channel length x exploiting several cutting planes y, z normal to the streamwise direction (x), and the temperature profile of the T_b along x has been interpolated through a linear function. The temperature T_{wall} has been mapped on the plane of the lower wall x, z and, together with the constant value of q applied there, the local convective heat transfer coefficient h_{xz} has been computed as $h_{xz} = q/(T_{wall_{xz}} - T_{b_{xy}})$, and then the corresponding Nusselt number Nu_{xz} as a consequence of h_{xz}. Lastly, the Nusselt number has been normalized between 0 and 1, considering the maximum and minimum values of the Nusselt number on the lower wall of the channel as $Nu_{01_{xz}} = (Nu_{xz} - \min(Nu_{xz}))/(\max(Nu_{xz}) - \min(Nu_{xz}))$.

Experimental data on the local convective heat transfer coefficient come from the IR-camera as described previously in 2.2. To compare the local Nusselt number with numerical values, the experimental distribution is subjected to an additional operation, we proceeded to normalize it between 0 and 1 as done for the CFD data. These contours are presented in figure 5; the area of the Nusselt in figure 5a appears smaller with respect to the area in figure 5b because the IR-image is not taken from a view-point exactly perpendicular to the channel, this causes a small shadow-area due to the presence of the ribs, so the area captured experimentally is reduced. Also the presence of lateral walls causes shadows and optical problems, therefore also the spanwise dimension of the analyzed area is reduced.

This comparison arises some criticality because of the different numerical and experimental resolutions, with the latter significantly lower than the first one. Consequently, LES simulations display structures that cannot be seen via experiments. However, it is possible to see, both in the CFD and experimental results, that near the side walls there is an increase in heat transfer coefficient due to the presence of ribs, whereas just downstream and upstream the ribs, heat transfer coefficient is lower.



(a) Experimental. **(b)** Numerical.

Figure 5. Local Nusselt number distribution, normalized between 0 and 1. The streamwise direction is from left to right.

4. Discussion and Conclusions

The results obtained from this work are promising in that at fluid-dynamic level for $Re = 1000$ it is possible to identify similar vortices and structures between numerical and experimental results. Regard convective heat transfer coefficient, at qualitative level Nusselt maxima and minima are comparable in term of area distribution. It's possible to conclude that LES can accurately predict heat transfer in ribbed channels and provide instant information on flow, temperature, and turbulence that RANS cannot. This enables a comprehensive understanding of the local heat transfer distribution process and facilitates the identification of mechanisms driving enhanced heat transfer. On the other hand, numerical and experimental comparisons appear to be rather problematic at low Reynolds numbers. Due to limitations of the actual experimental setup, it was not possible to analyse flow fields at Reynolds number higher than presented, values for which they instead seem to be better modeled by CFD. Hence, we need to improve both the experimental setup and the numerical model to have results for a wider range of Reynolds, i.e., between about 500 and 8000. As regards the experimental setup for fluid-dynamic analysis, brightness of the flow field images must be enhanced to avoid capturing images too dark or blurred. As regards the numerical model, other sub-grid scales models, besides the dynamic Smagorinsky, must be investigated to confirm its effectiveness for this kind of problems with respect to others sub-grid scales models. In addition, we need to understand whether it's necessary adding synthetic turbulence at low Reynolds number, while maintaining the present computational grid, or we must just manage to solve properly the fluid flow by further thickening the computational grid. Probably, also a DNS at low Reynolds number, in the case it captured the turbulence, should give an answer on adding a synthetic turbulence to LES. Finally, we are expecting to carry out a domain sensitivity analysis to analyse if a more or less extended periodic domain, in streamwise direction, affects results. In conclusion, results appear very promising although much further work is needed both on the experimental setups and numerical models. Many of these activities are already ongoing.

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